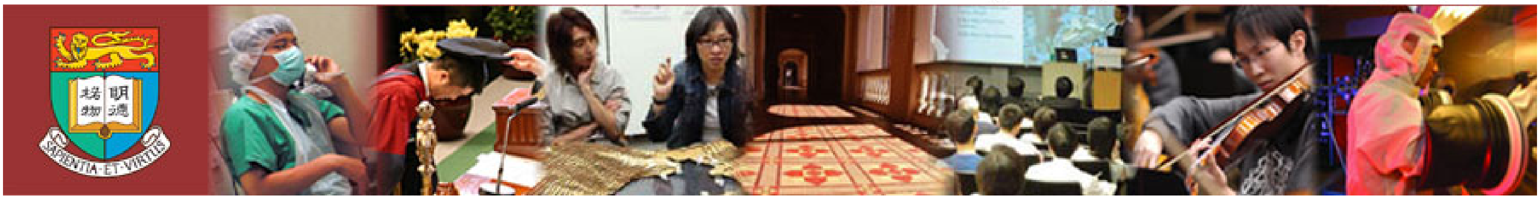

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Author(s)	Xu, JJ; Zhang, C; Xu, JB; Wong, KKY; Tsia, KK
Citation	The 2014 OSA Biomedical Optics (BIOMED) Meeting, Miami, Florida, USA, 26-30 April 2014.
Issued Date	2014
URL	http://hdl.handle.net/10722/204126
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Demonstration of amplified optical time-stretch optical coherence tomography (AOT-OCT) in the magehertz A-scan rate regime

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Abstract: We report megahertz (1.2–7MHz) optical coherence tomography based on amplified optical time-stretch – showing superior roll-off performance (>2mm/dB), a record-high sensitivity of time-stretch-based OCT (80-90dB), with 80nm broadband gain bandwidth.
OCIS codes: (110.4500) Optical coherence tomography; (170.3880) Medical and biological imaging; (190.5650) Raman effect.

Optical coherence tomography (OCT) is a powerful optical imaging modality for cross-sectional assessment of biological tissue with micrometer resolution and high detection sensitivity. Because of its non-invasiveness, OCT has been found useful in many clinical applications including ophthalmology, dermatology and gastroenterology to name a few. In many occasions, these applications demand for three dimensional (3D) imaging at video-rate in order to perform real-time diagnoses. Such image acquisition rate requires ultrafast A-scan rate of more than MHz. So far, the most viable approach to achieve high-speed OCT is Fourier-domain OCT (FD-OCT) which can be further classified into two main categories: spectral-domain OCT (SD-OCT) and swept-source OCT (SS-OCT). The speed of SD-OCT depends on the acquisition speed of the image-sensor-based spectrometer which is technologically challenging to go beyond ~ 100 – 200 kHz [1, 2]. In contrast, SS-OCT has been shown promising for practical MHz OCT imaging. SS-OCT systems based on Fourier-domain mode locked (FDML) laser and polygonal rotating mirror have been demonstrated with 100’s kHz fundamental A-scan rate [3, 4]. Add-on features, such as multi-spot illumination and fiber buffering, can further boost the speed of SS-OCT to the MHz regime [5]. Notably, the swept source based on vertical cavity surface-emitting laser (VCSEL) has also recently been shown to achieve 1 MHz A-scan rate for high-speed OCT [6]. However, the mechanical inertia and instability of the moving parts in the aforementioned swept sources intrinsically limit the speed of OCT and also hinder robust operation in long-term.

Another attempt to realize MHz OCT is to implement an all-optical swept-source based on optical time-stretch. This is an optical process which maps the wavelength spectrum of a broadband laser pulse into time via group velocity dispersion (GVD) in a dispersive fiber. In this way, the broadband pulse is optically wavelength-swept (or time-stretched) by GVD without mechanical wavelength tuning. The A-scan rate is governed by the repetition rate of the laser pulse train, which is typically ~10’s MHz for most of the pulse laser sources. Although previous work on time-stretch-based OCT shows that the A-scan rate well beyond 10’s MHz can be easily achieved [7-10], they are unable to capture high-quality images for biological tissue. This is mainly due to insufficient sensitivity (because of the significant GVD loss) and poor axial resolution (due to the narrow bandwidth of the source) in these time-stretch-based OCT systems. Here we present a major advancement in time-stretch-based OCT, called amplified optical time-stretch OCT (AOT-OCT), which achieves broadband hybrid optical amplification (>80nm) in order to overcome the fundamental trade-off between optical loss and GVD[11]. It also shows the superior roll-off performance (>2mm/dB). As a result, the inertia-free AOT-OCT reported here, showing significant improvement over our earlier work and others [7-10], holds promise as another viable route for practical MHz OCT with high sensitivity (>80 dB) and resolution (15 μm).

Figure 1 shows the experimental setup of AOT-OCT system. The picosecond laser generates a train of pulses at 1554.8 nm wavelength with 5 ps pulse width and 7.14 MHz repetition rate. With peak power of ~ 200 W, the laser pulse is pumped into a 50 m highly-nonlinear fiber (HNLF) (zero-dispersion wavelength: 1554nm) for the generation of a broadband supercontinuum (SC). Then the SC is coupled into a 10.6 km dispersion compensation fiber (DCF) with a total GVD of ~ 1 ns/nm for time-stretch. To compensate the optical loss in DCF and provide a broadband optical gain for SC, we also employ four Raman pumps at different wavelengths in this DCF in both forward and backward pump directions. After this amplified time-stretch process, we use a booster optical amplifier (BOA) to further amplify the stretched pulse. Hence, the sensitivity of OCT imaging within a broadband spectrum

(>80nm) can be enhanced. The wavelength-swept pulses generated by AOT are subsequently launched into a fiber-based Mach–Zehnder interferometric setup. The resultant inteferograms are finally detected by a single high-speed photodetector (PD) (15 GHz bandwidth) and a real-time oscilloscope with a sampling rate of 80GS/s. We use a delay line (DL) to balance the optical path length difference between the reference and sample arm and employ a one-dimensional scanning mirror to generate the cross-sectional OCT image.

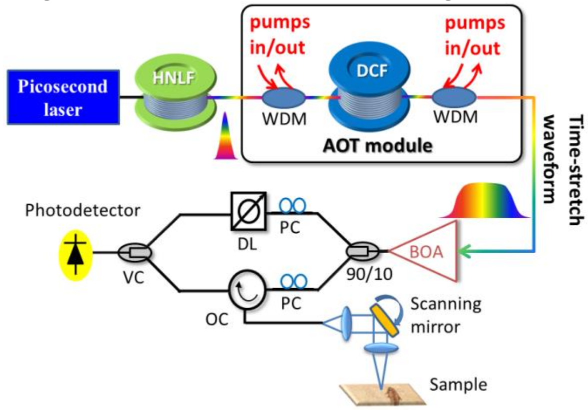

Fig. 1. Experimental setup of the AOT-OCT system. HNLF: highly-nonlinear fiber, WDM: wavelength-division multiplexer, DCF: dispersion compensation fiber, BOA: booster optical amplifier, PC: polarization controller, DL: delay line, OC: optical circulator, VC: variable coupler.

After SC generation of SC in the HNLF, a spectral range from 1570 nm to 1700 nm is selected by a wavelength-division multiplexer (WDM), as the imaging source of the AOT-OCT system. The black curve in Fig. 2(a) shows the flat and broadband spectrum of this filtered SC after time-stretch in the DCF. We apply multiple-pump fiber Raman amplification which provides broadband optical gain with low noise figure together with a BOA in order to compensate the deterioration of signal-to-noise ratio (SNR) because of the GVD loss. And thus the sensitivity could be enhanced. A broadband gain of ~ 25 dB with the gain bandwidth of ~ 80 nm is achieved in the AOT-OCT system, as shown by the red curve in Fig. 2(a). Fig. 2(b) shows the time-stretch interferograms captured by the real-time oscilloscope. With an average GVD of ~ -1 ns/nm, the full swept range of 120 nm (1570 nm – 1690 nm) is mapped into a time span of ~ 120 ns – corresponding to a ~100% duty cycle with a swept-rate of 7.14MHz. The single shot point spread function (PSF) is measured to be ~ 15 μm, which agrees well with the theoretical calculation of 14 μm, assuming a Gaussian spectral shape with a full-width half-maximum of 80 nm centered at 1620 nm. With an illumination power of ~10 mW onto the sample, the sensitivity of current system is measured to be as high as ~82 dB at 7.14 MHz A-scan rate. This is, to the best of our knowledge, the highest sensitivity among all the existing time-stretch-based OCT approaches [7-10]. Notably, because of the large GVD in our system, the roll-off number is as high as 2.2 mm/dB up to the depth at ~15 mm. This is ~20 times better than that of FDML-OCT at a similar speed of 5.2 MHz effective swept rate [5]. The calculated instantaneous linewidth is 132 pm, based on stationary- phase approximation in the AOT process [11]. It corresponds to an instantaneous coherence length as long as ~1 cm which is consistent with the roll-off performance. Note that the roll-off drops quickly beyond 20 mm because of the frequency response of the photodetector, with a bandwidth of 15 GHz.

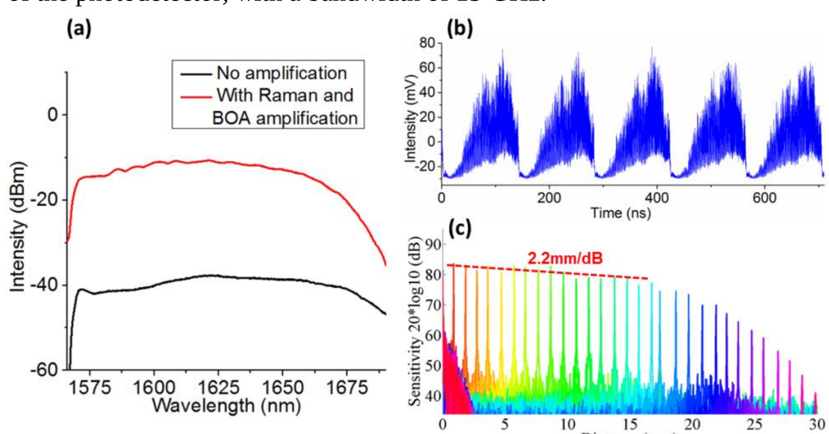

Fig. 2. (a) Time-stretch spectra without any amplification (black) and with both Raman amplification and BOA (red). (b) Real-time interferograms at a rate of 7.14MHz. (c) Roll-off performance of AOT-OCT measured in air.

The ultra-high fundamental A-scan rate of AOT-OCT system enable us to perform averaging in order to further improve the image quality without seriously compromising the speed. Here we take 6 averaging for consecutive A-scans, which results in an improved sensitivity of ~ 90 dB with an effective A-scan rate of 1.2 MHz. Figures 3(a) and (b) show the AOT-OCT images of human finger print and the anterior segment of the fish eye, respectively. We can observe the dermis as well as sweat ducts beneath epidermis of human finger in Fig. 3 (a). Fig. 3 (b) also reveals the structure of cornea, iris, epithelium and endothelium in the eye of fish. We stress that such *in vivo* biological tissue imaging at MHz A-scan rate by AOT-OCT is only made possible in the presence of broadband amplification together with the time-stretch process – the major attribute of this technique. Finally, Table 1 shows the comparison of the key high-speed OCT systems, including the present AOT-OCT system. Two main improvements can be made to further advance the technique for practical biological tissue imaging. First, broadband and high-gain amplifier designs in terms of lower noise figure are essential to operate the system approaching to its shot-noise limit. Second, the spectral fluctuation of the broadband source, which lowers the sensitivity, has to be minimized. This can be done by employing femtosecond SC [12], seeded SC [13], or normal-dispersion-pumped SC in a dispersion-engineering HNLF [14]. We thus anticipate that the present work on AOT-OCT, along with the advances in broadband laser sources and fiber amplification, could open a new practical alternative for realizing MHz OCT.

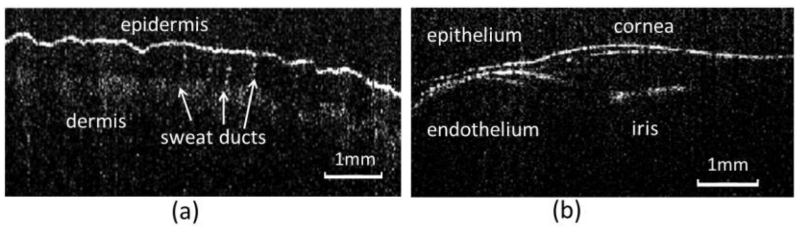

Fig. 3. (a) AOT-OCT images of (a) the anterior segment of the fish eye and (b) human finger print.

Table 1 Comparison of the key high-speed OCT systems

	FDML-OCT [5]	**Time-stretch-OCT [7]**	**AOT-OCT**
Fundamental A-scan rate	325 kHz	5 MHz	7.14 MHz
Effective A-scan rate	5.2 MHz (fiber buffering)	5 MHz	1.2 MHz (average by 6)
Sensitivity	98 dB	40 dB	90 dB
Sweep range	80 nm	200 nm	80 nm
Axial resolution	13 μm	8 μm	15 μm
Power on sample	4×25 mW	~0.4mW	10 mW
Linewidth (FWHM)	240 pm	Not applicable	132pm
R number (roll-off)	0.10 mm/dB	Not applicable	2.2 mm/dB

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